

Measuring θ_{12} Despite an Uncertain Reactor Neutrino Spectrum

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Abstract

The recently discovered 5 MeV bump highlights that the uncertainty in the reactor neutrino spectrum is far greater than some theoretical estimates. Medium baseline reactor neutrino experiments will deliver by far the most precise ever measurements of θ_{12} . However, as a result of the bump, such a determination of θ_{12} using the theoretical spectrum would yield a value of $\sin^2(2\theta_{12})$ which is more than 1% higher than the true value. We show that by using recent measurements of the reactor neutrino spectrum the precision of a measurement of θ_{12} at a medium baseline reactor neutrino experiment can be improved appreciably. We estimate this precision as a function of the ^9Li spallation background veto efficiency and dead time.

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1 Introduction

In about 5 years the largest liquid scintillator detectors ever built will be used to detect reactor neutrinos at the experiments JUNO [1] and RENO 50 [2]. The often-stated goal of these experiments is the determination of the neutrino mass hierarchy, following the strategy of Petcov and Piai [3]. Obtaining the required precision for a determination of the hierarchy will be very challenging [4, 5, 6]. On the other hand, whether or not this precision can be achieved, there is no doubt that such experiments can provide by far the most precise measurement yet of θ_{12} [7].

In this note we will show that imperfect knowledge of the reactor neutrino spectrum is a leading source of uncertainty in the measurement of θ_{12} and that this uncertainty has been systematically underestimated in the literature. Studies of this measurement use the latest reactor neutrino flux model from Ref. [8]. They also use the uncertainties quoted in that paper. Nonetheless, as the author clearly stated in Ref. [9], the uncertainty quoted in Ref. [8] reflects only a subset of the sources of uncertainty in the analysis and so in fact yields only a lower bound on the true uncertainty. Indeed, a widely accepted explanation for the reactor anomaly of Ref. [10] is that the uncertainty of reactor neutrino fluxes is systematically underestimated.

Our analysis will yield its own estimate of the expected uncertainty in θ_{12} . While this estimate is necessarily quite precise, it will not be accurate. An accurate determination would require the full covariance matrix of uncertainties for the spectrum generated by each isotope 10 years from now, when the data from these experiments is analyzed. However such a covariance matrix or isotope by isotope analysis is not available even now.

Our motivation for writing this paper now, when the covariance matrix for the uncertainties is not yet available, is as follows. In a companion paper [11] we consider the tracking requirements for cosmogenic muons for such experiments. For this, we need to know not the absolute value of the uncertainty in θ_{12} , but rather its expected dependence on the background rejection efficiency. While the absolute value of the uncertainty that we will obtain is quite approximate, the current paper nonetheless demonstrates that the uncertainty in θ_{12} receives a large contribution from systematic errors. This means that little is lost by increasing the statistical fluctuations via a veto strategy with a large dead time. In Ref. [11] we demonstrate that, as a consequence, a very high spallation background rejection efficiency is optimal for the θ_{12} measurement, higher than that for the mass hierarchy. This result is

quite robust.

2 The Theoretical Uncertainty has been Underestimated

In this subsection we will motivate our new analysis of the precision of a measurement of θ_{12} by showing that the uncertainty in the theoretical spectrum [8], which has been used in previous determinations of the precision, was greatly underestimated. Our new study, which will be the subject of Sec. 3, will therefore provide a somewhat more reliable determination of this precision.

Recently a 5 MeV bump in the ratio of the measured reactor neutrino spectrum to the theoretical spectrum of [8] has been observed by RENO [12, 13], Double Chooz [14] and Daya Bay [15]. The amplitude of this bump is more than 10%, corresponding to 4σ in terms of the theoretical reactor flux uncertainties of Ref. [8]. Therefore it is clear that the difference between the true reactor spectrum and that of Ref. [8] is appreciably larger than the subset of the uncertainties which were quantified in that work.

To reassess the validity of a determination of the precision of a measurement of θ_{12} based on the theoretical spectrum, we will now answer the following question: What effect does the bump have on a determination of θ_{12} ?

Let us fix the neutrino mass splittings to be

$$\Delta M_{31}^2 = 2.4 \times 10^{-3} \text{eV}^2, \quad \Delta M_{21}^2 = 7.5 \times 10^{-5} \text{eV}^2 \quad (2.1)$$

with the normal mass hierarchy and the relevant neutrino mixing angles to be

$$\sin^2(2\theta_{13}) = 0.089, \quad \sin^2(2\theta_{12}) = 0.857. \quad (2.2)$$

We normalize the $\bar{\nu}_e$ flux at JUNO by setting the number of IBD events to be 10^5 for a 6 year run at a baseline of 58 km, but we adapt the correct baselines from Ref. [1].

For the calculation of χ^2 , in addition to θ_{12} , we minimize three pull parameters corresponding to the flux normalization of the spectrum and background, with uncertainties of 5% and 1% respectively, and also the value $\sin^2(2\theta_{13})$ with an uncertainty of 0.01. Variations of the later two uncertainties have little effect on our results. Then, assuming a perfectly understood nonlinear energy response for the detector and no backgrounds, we find that if the true reactor spectrum is that observed by Daya Bay in Ref. [15] but it is fit to the theoretical spectrum of Ref. [8] then the lowest χ^2 fit would arise with a value of $\sin^2(2\theta_{12})$ which is more than 0.01 too high. This is because it leads to less events at the solar oscillation maximum, around 3 MeV, and more events at higher energies, away from the maximum.

By comparison, studies in the literature on the precision of a measurement of $\sin^2(2\theta_{12})$ using the uncertainty reported in Ref. [8] estimate a precision of, for example, 0.3% including the uncertainty caused by a model of the detector's nonlinear energy response [16]. Thus, were θ_{12} determined using the theoretical model [8] of the reactor spectra then the value obtained would differ from the true value by four times the uncertainty reported in, for instance, Ref. [16].

One might object that it is obvious that, now that the bump has been discovered, one should use the spectrum with the bump for all analyses. This is of course true. However it means that a new analysis is needed of the precision with which θ_{12} can be determined. This is the goal of the present paper.

3 The Uncertainty with which θ_{12} may be Measured

In this note we would like to observe that the precise measurements of the reactor spectrum by the Daya Bay [15] and at the RENO near detector [13] in fact allow for a precise determination of θ_{12} . An accurate determination of the uncertainty which may be expected in θ_{12} would require, for each isotope, a covariance matrix of the errors in Refs. [15]. Such a set of covariance matrices is not available. So we simply sum in quadrature the bin per bin statistical and systematic errors reported by Daya Bay and treat them as uncorrelated.

As the entire spectrum, as measured at JUNO or RENO 50, corresponds to only half of a 1 – 2 flavor oscillation, only such broad features of the spectrum will be important for measuring θ_{12} . Therefore even if the underlying reactor spectrum has a rich structure at scales of order 200 keV or smaller, which was not observed in Ref. [15] due to binning and the finite energy resolution, this will have no effect on the determination of θ_{12} . On the other hand the determination of the hierarchy depends on 1 – 3 oscillations which have a much shorter wavelength and so may be affected by such a substructure in the reactor spectrum [17], an effect which may even be amplified by the self-calibration of Ref. [1].

The reactor neutrino experiment JUNO will have a very different baseline and total reactor flux from Daya Bay. This leads to different oscillation probabilities. However, the different oscillation probabilities only affect the normalization of the number of events observed in each bin, and not the fractional uncertainty in the reactor flux. Therefore, ignoring the somewhat distinct isotope ratios, the fractional uncertainty in the spectrum at each bin at JUNO will be equal to that at Daya Bay.

To estimate the effect of the unknown spectrum on the determination of θ_{12} , we proceed as follows. First, we determine the shape of the deformation of the reactor spectrum which

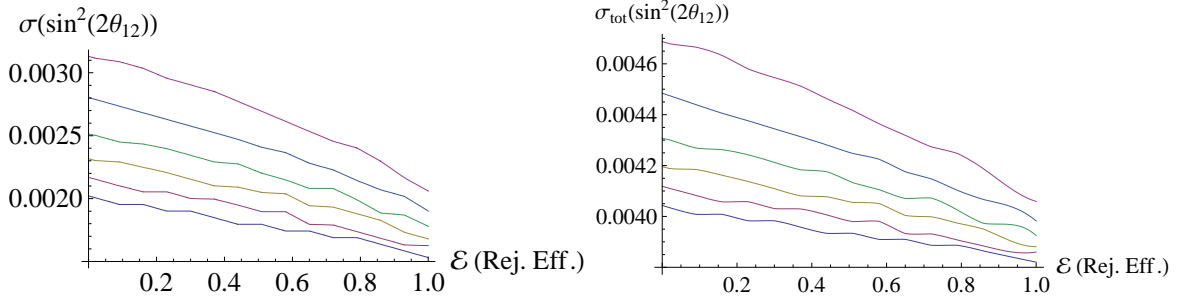


Figure 1: The horizontal axis is the ${}^9\text{Li}$ rejection efficiency. Each curve represents a different dead time, in ascending order from 0% to 50% in steps of 10%. **Left:** The uncertainty σ in the best fit value of $\sin^2(2\theta_{12})$, assuming a perfectly understood reactor spectrum, optimizing all pull parameters to minimize χ^2 . **Right:** The sum in quadrature σ_{tot} of the uncertainty σ and the shift $\delta(\sin^2(2\theta_{12}))$.

would simulate in a shift

$$\theta_{12} \rightarrow \tilde{\theta}_{12} = \theta_{12} + \delta\theta_{12} \quad (3.1)$$

at JUNO. With a single detector JUNO can never distinguish such a shift in the reactor spectrum from a shift (3.1) in θ_{12} . We fix the value of $\delta\theta_{12}$ such that such a shift in the reactor spectrum fits Daya Bay's determination of the spectrum with $\chi^2 = 1$, using the uncertainties reported in Ref. [15]. This yields an expected systematic shift in JUNO's measurement of $\sin^2(2\theta_{12})$ of

$$\delta(\sin^2(2\theta_{12})) = 0.0035. \quad (3.2)$$

Note that the various degeneracies between the reactor flux uncertainty and uncertainties in the mixing angles, backgrounds, etc. do not affect this calculation, because the χ^2 value of the Asimov data at JUNO with the shifted reactor flux is equal to 0, since the shift in the spectrum has been chosen such that it can be precisely compensated by a shift in θ_{12} .

The uncertainty in the reactor flux is not responsible for all of the expected uncertainty in θ_{12} . To determine other contributions to the precision of a measurement of $\sin^2(2\theta_{12})$, we fix the reactor flux to the model of Ref. [8] and use the Asimov data set to determine the value of $\sin^2(2\theta_{12})$ for which, when choosing the pull parameters of Sec. 2 to minimize χ^2 , one obtains $\chi^2 = 1$ after 6 years. The only background that we consider is cosmogenic ${}^9\text{Li}$ with the rate given in Ref. [18]. We assume that this background can be rejected with an efficiency \mathcal{E} , yielding a fractional dead time. Various fractional dead times are considered. We assume that the nonlinear energy response of the detector is perfectly understood, although in practice the uncertainty in the nonlinear energy response will yield a significant contribution to the uncertainty in θ_{12} [16].

This procedure yields the uncertainty in θ_{12} not including the contribution from the uncertain reactor flux. The resulting 1σ uncertainties are summarized in the left panel of Fig. 1. In the right panel we add the result in quadrature to $\delta(\sin^2(2\theta_{12}))$ to obtain the final uncertainty $\sigma_{\text{tot}}(\sin^2(2\theta_{12}))$. As can be seen, using the recent measurements [13, 15] one can reduce the uncertainty in $\sin^2(2\theta_{12})$ to about 0.5%, which is roughly in line with the stated goals of the experimental collaboration. A more precise measurement of the reactor spectrum in the future may reduce this [17], but not beyond the uncertainty displayed in the left panel of Fig. 1.

To determine the precision of a measurement of $\sin^2(2\theta_{12})$ if the third and fourth Taishan reactors are not built is straightforward. These account for 26% of the total thermal power expected at the Taishan and Yangjiang reactor complexes. Therefore one can read the resulting uncertainties off of Fig. 1 by replacing the dead time τ by

$$\tau' = 0.76\tau + 0.24. \quad (3.3)$$

4 Remarks

At first glance the fact that our final precision is of the same order as that obtained in previous studies might suggest that this analysis has been trivial. However we would like to point out that this coincidence is accidental, caused by the fact that the theoretical uncertainties of Ref. [8] are similar in magnitude to last year's observational uncertainty [13, 15]. Had we used older data, or last year's data from Double Chooz [14] then the new uncertainty would have been much larger. Indeed the two analyses are quite different. Traditional estimates of the precision of a measurement of θ_{12} , such as that in Ref. [16], are quite precise as they use the uncertainty in [8] for which the full covariance matrix is given. However, for an analysis using the theoretical spectrum of Ref. [8], they are nonetheless inaccurate as that uncertainty was always intended as a lower bound and is now known to be smaller than the true uncertainty by a factor of four. On the other hand, as the uncertainties in our analysis are observational, there is no such bias. Nonetheless, as we do not have a covariance matrix for these uncertainties, we assumed that the uncertainties are uncorrelated and thus our estimated uncertainty JUNO's measurement of θ_{12} is lower than may be expected were JUNO to run today. On the other hand, Daya Bay and RENO continue to improve the precision of their measurements of the reactor flux, which will reduce the uncertainty in θ_{12} which will be attained by JUNO, but not beyond that reported in the left panel of Fig. 1.

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